Patent Application of

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for

TITLE: CONCRETE PAVEMENT WITH THE PRESET STRENGTH SAFETY LEVEL FOR HIGHWAYS AND STREETS

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FEDERALLY SPONSORED RESEARCH

Not Applicable

SEQUENCE LISTING PROGRAM

Not Applicable

BACKGROUND – FIELD OF INVENTION

This invention relates to the field of design and construction of highway and street concrete pavements.

BACKGROUND – DESCRIPTION OF PRIOR ART

The design of highway and street concrete pavements in US building practice is usually carried out according to the Portland Cement Association Engineering Bulletin (Thickness Design of Concrete Highways and Street Pavement, Portland Cement Association, EB109P). The purpose of the thickness

design of these pavements according to said Engineering Bulletin is "to find the minimum thickness that will result in lowest annual cost as shown by first cost and maintenance costs." It presumes the conduction of the thickness design procedure of pavement with preset strength safety level of this pavement and corresponding allowable estimation of probability of failure, i.e. the probability of cracking as applied to concrete pavement.

Estimations of the strength safety of structural members are usually expressed by the strength safety index β. Values of the strength safety index β equal to 2, 2.5 and 3 correspond to estimations of strength safety equal to 0.9772,0.9938 and 0.9986, respectively. The estimation of strength safety of a structural member corresponding to value of strength safety index β equal at least to 3 is usually considered close to 1 in the engineering applications of such types. Estimations of strength safety as a function of the strength safety index β are determined by the Table of normal distribution of density of probability presented in all reliability handbooks (Grant E.L. Statistical Quality Control, 3d ed., 1964, McGraw-Hill, for example).

The preset strength safety level of concrete pavement of highways and streets should be chosen on the basis of analysis of the existing strength safety level of real structural members, since the practice is the only criterion of strength safety. The few considerable samplings of test results of underreinforced prestressed floor and roof slabs of multi-story building frames, mainly prestressed hollow-core slabs, can be used for the estimation of existing strength safety level of real structures. These slabs were designed according to the Russian building code, produced and tested at the Russian plants of precast concrete; Russian construction is based on the use of precast concrete, and the Russian building code requires regular tests of these structural members, mainly floor and roof slabs. Furthermore, the estimation of strength safety of these slabs was compared with the estimation of strength safety of columns, which is based on the test results of 111 axially loaded reinforced concrete columns of multi-story building frames produced on the Moscow plants (Sapozhnikov N. Strength

Safety of Precast Reinforced Concrete and Prestressed Structural Members. State Committee of Construction of the USSR Institute of Information, Moscow, 1989, Tables 12 and 24).

Estimations of the strength safety level of these members as probabilities $P(M_{fail}^{test} > M_{des}^{SNiP})$ are presented in form of strength safety index β, with the value of M_{des}^{SNiP} considered the design moment strength of member, i. e. factored moment according to current Russian code. Estimations of the strength safety of these slabs correspond to the values of strength safety indexes β in the range of 2.15 to 3 for samplings of test results of slabs of one type but with different spans produced at different plants. Estimations of the strength safety of these slabs produced at one plant correspond to values of strength safety indexes β in the range from 2.5 to 3, and the strength safety level of these slabs is no less than that of reinforced columns of these multi-story building frames. These estimations of strength safety can be applied to the American building practice by comparison of strength design of underreinforced slabs floor and roof according to American and Russian building codes.

To apply this data to the American building practice it is necessary to compare the strength design of the same underreinforced flexural members according to the American building code ACI 318 and the Russian building code. Service loads in American building codes are higher than those in Russian building codes, but due to the Russian design practice of unification of loads on the floor slabs and the use of floor slabs as roof slabs, this difference is practically negligible. The load factors in strength design are significantly higher in American building codes than those in Russian building codes (1.4 and 1.1 for dead loads, 1.7 and 1.2 - 1.3 for live loads in the American and Russian building codes, respectively). As a result, the factor loads for floor slabs designed according to the American building code ACI 318 are higher at least by 28.5% than that for slabs with the same dimensions under the same service loads designed according to the Russian current building code. For underreinforced flexural members, the increase of the factor moment means the corresponding increase of consumption of tension reinforcement.

The capacity of underreinforced floor and roof slabs is determined almost completely by the strength of tension reinforcement. The strength safety of these members is estimated in the form of probability $P(M_{capacity} > M_{des})$, where $M_{capacity}$ is the capacity of flexural member as a moment strength considered as a random value and M_{des} is the design strength of this member defined as a factored moment strength (required moment strength of member) determined according to the current building code. This probability presented in the form $P(M_{capacity} / M_{des}>1)$ is more suitable for the estimation of the strength safety of flexural members. The mean value of the ratio $M_{capacity} / M_{des}$ is an important and suitable index of strength safety of these structural members.

The consumption of tension reinforcement in an underreinforced flexural member is determined by the value of the required moment strength. The increase of this strength requires a proportional increase in the consumption of tension reinforcement of member and a corresponding increase of the mean value of capacity of this flexural member $M_{capacity}$. As a result, the mean value of the ratio $M_{capacity} / M_{des}$ of an underreinforced flexural member varies only slightly with the change of consumption of tension reinforcement. As applied to floor and roof slabs, the ratio $M_{capacity} / M_{des}$ is practically constant for slabs with similar dimensions but with different consumption of tension reinforcement until these slabs can be considered as underreinforced members with a small influence of concrete strength on the flexural strength of member.

Estimations of the strength safety of similar floor and roof slabs designed according to thee American and Russian building codes can be defined as the probabilities $P(M_{capacity}^{ACI}/M_{des}^{ACI}>1)$ and $P(M_{capacity}^{SNiP}/M_{des}^{SNiP}>1)$, respectively. The values of ratios $M_{capacity}^{ACI}/M_{des}^{ACI}$ and $M_{capacity}^{SNiP} / M_{des}^{SNiP}$ are close, and the estimations of probabilities $P(M_{capacity}^{ACI}/M_{des}^{ACI}>1)$ and $P(M_{capacity}^{SNiP}/M_{des}^{SNiP}>1)$ should be close also. At the same time, the probability $P(M_{capacity}^{ACI}> M_{service})$ for slabs designed according to ACI 318 is higher significantly than probability $P(M_{capacity}^{SNiP} > M_{service})$ for slab designed according to Russian building code. $M_{service}$ is considered

as service moment strength the same for slabs designed according to American and Russian building codes.

It is apparent that the real strength safety level of underreinforced slabs designed according to the American current building code ACI 318 is significantly higher than that for the same slabs designed according to the Russian building code. However, the formal estimations of strength safety of these underreinforced slabs designed according to American and Russian building codes are practically the same. It allows one to use results of strength safety analysis of underreinforced prestressed floor and roof slabs designed according to the Russian building code, produced and tested at the Russian plants for the choice of preset strength safety of concrete pavement of highways and streets.

The minimum strength safety level of structural members relates to the precast reinforced and prestressed concrete slabs of temporary roads considered as structures with economical responsibility (Berdichevsky G.I, Sapozhnikov N.Ya. Design Features of Bent Concrete Constructions with the Economical Responsibility. Moscow, 1982, The Ninth International Congress of FIP, Stockholm, June 6-18, 1982, USSR. Member Group). The strength design of these slabs with the preset strength safety level corresponding to the strength safety index β equal at least to about 2 allows a reduction of tension reinforcement by around 15%. The sufficiency of the strength safety level of these slabs is justified by their 20-year operation. Reinforced and prestressed road slabs are considered as underreinforced structural members, and estimations of strength safety of these slabs can be applied to American building practice as well as for prestressed floor and roof slabs.

Estimation of strength safety of concrete pavements requires the use of statistical characteristics of flexural strength of concrete. These statistical characteristics of the concrete strength were investigated in connection with the statistical characteristics of the compressive strength of this concrete, since compressive strength is the natural quality of concrete more commonly used and significantly better understood than flexural strength. This investigation was carried out by the

processing of the data of the American test results of compressive, flexural and axially tensioned concrete samples, and a small portion of British test results of modified cubes and standard beams (Sapozhnikov N. Safety of Precast Reinforced Concrete and Prestressed Structural Members by the Second Limit State (Serviceability Limit State). State Committee of Construction of the USSR Institute of Information, Moscow, 1991, Table 6).

Two large samplings of test results of compressive and flexural strength of concrete include 3650 series of test results of standard cylinders and beams 1107 series of test results of modified cubes and standard beams. These test results were used for the analysis of statistical connections between the compressive and flexural strength of concrete. These connections can be estimated as statistically significant; coefficients of correlation between the cylinder strength and the flexural strength of concrete, between the modified cube strength and the flexural strength of concrete are equal to 0.831 and 0.864, respectively. These values of the coefficient of correlation allow one to consider the statistical characteristics of flexural strength of concrete as stemming from those for the compressive strength of this concrete.

Flexural strength is not an inherent quality of concrete unlike compressive strength, and design estimations of flexural strength are assessed with extreme caution. It can be seen by the example of estimation of safety of permissible flexural stress used for the calculation of the cracking moment of prestressed flexural members according to said American building code ACI 318. Permissible flexural stress for concrete of prestressed members given to control of serviceability is equal to $6\sqrt{f_c'}$ according to said building code ACI 318 (item 18.4.2 c), where f_c' is the specified compressive strength of concrete. Since the cracking design of prestressed members is related to serviceability limit state, the value of permissible flexural stress of concrete equal to $6\sqrt{f_c'}$ can be considered as specified flexural strength of this concrete. The safety of this value of specified flexural strength can be assessed as a probability $P(f_r > 6\sqrt{f_c'})$, where the flexural strength f_r is considered as a random value. As a first

step for estimation of this probability with the use of test results of concrete, the probability $P(f_r > 6\sqrt{f_c})$ was calculated with the use of 3650 American test results of standard concrete cylinders and beams, with f_r and f_c being the actual values of flexural and compressive strength of same concrete. The empirical estimation of this probability is equal to 0.9952, and this value of probability corresponds to strength safety index β equal to 2.59 (Sapozhnikov N. Safety of Precast Reinforced Concrete and Prestressed Structural Members by the Second Limit State (Serviceability Limit State). State Committee of Construction of the USSR Institute of Information, Moscow, 1991, page 47).

According to said American building code ACI 318 (item 5.3.2.1) the required average compressive strength of concrete should exceed the specified compressive strength of this concrete f_c' by at least by 25%, if coefficient of variation of this strength is assumed to be 15%. Considering the experimental value of compressive strength of concrete f_c as average, the specified compressive strength of this concrete f_c' can be estimated to be 25% less. Taking into account this difference between f_c' and f_c, the probability $P(f_r > 6\sqrt{f_c'})$ can be estimated conventionally as corresponding to strength safety index β equal to 2.88. It seems useful to compare this estimation of safety of permissible flexural stress considered as a specified flexural strength of concrete with the safety of the specified and the design compressive strength of concrete and the yield strength of tension reinforcement.

According to said American building code ACI 318, the specified compressive strength of concrete f_c' constitutes approximately 0.8 of mean value of this strength, and the safety of specified strength corresponds to strength safety index β equal to 1.34. Design compressive strength of concrete for underreinforced flexural members can be estimated as $\phi f_c'$, where ϕ is strength reduction factor equal to 0.9 (ACI 318 building code, item 9.3.2.1). Design compressive strength of concrete for axially loaded columns with tie reinforcement conforming can be estimated as 0.476 of specified compressive strength f_c' (ACI 318 building code, item 10.3.5.2).

The safety of design compressive strength of underreinforced floor and roof slabs corresponds to value of strength safety index β equal to 1.87, whereas the safety of design compressive strength of axially loaded reinforced concrete columns corresponds to value of strength safety index β equal to 4.13, with the coefficient of variation of compressive strength of concrete assumed to be 15%. This difference can be justified by the different requirements of the concrete strength of underreinforced floor and roof slabs and reinforced concrete columns of a multi-story building frame.

The mean value and standard deviation of yield strength of deformed bars Grade 60 ASTM A615 used as tension reinforcement of floor and roof slabs are equal to 67.5 and 6.6 ksi, respectively (MacGregor J.G., Mirza S.A., Ellingwood B., Statistical Analysis of Resistance of Reinforced and Prestressed Concrete Members. American Concrete Institute Journal, Proceedings vol.80 May-June 1983/No. 3 pp. 167-176, Table1). The ratio between specified yield strength and main value of yield strength of this reinforcement is equal to 0.888. The safety of specified yield strength of this reinforcement is defined as a probability $P(F_y > f_y)$, where F_y is the yield strength considered as a random value and f_y is the specified yield strength equal to 60 ksi. The estimation of this probability corresponds to strength safety index β equal to 1.14.

The design strength of deformed bars ASTM A615 as tension reinforcement of underreinforced floor and roof slabs can be estimated approximately as ϕf_y, where f_y is the specified yield strength of reinforcement, ϕ is the strength reduction factor equal to 0.9 (ACI 318 building code, item 9.3.2.1). The safety of the design yield strength of this reinforcement defined as a probability $P(F_y > \phi f_y)$ corresponds to strength safety index β equal to 2.05.

Thus, the strength safety level of permissible flexural stress of concrete used for the estimation of cracking resistance of prestressed members under service loads according to said American building code ACI 318 is very high. It is significantly higher than the safety of the specified and design compressive strength of concrete of flexural underreinforced members and the safety of

specified and even design strength of deformed bars Grade 60 ASTM A615 used as tension reinforcement of underreinforced floor and roof slabs. The probability of compressive strength less than specified one is higher by 45 times than that for permissible flexural strength of concrete of prestressed members. Estimation of the strength safety level of permissible flexural stress of concrete is a value of the same order as the safety of compressive strength of axially loaded columns. A very high strength safety level of permissible flexural stress of concrete means the underestimation of flexural strength of concrete as a random value and a low level of the utilization of this strength.

A low level of the utilization of the flexural strength of concrete and high strength safety level of estimations of the design flexural strength of concrete are not related only to the American building practice. The analysis of the safety of the cracking resistance of prestressed flexural members designed according to the current Russian building was carried out basing on the processing of the data of more than 2,000 test results of these members (Sapozhnikov N. Safety of Precast Reinforced Concrete and Prestressed Structural Members by the Second Limit State (Serviceability Limit State). State Committee of Construction of the USSR Institute of Information, Moscow, 1991, Table 4). The estimation of the safety of the cracking resistance of prestressed flexural members under service loads can be defined as a probability $P(M_{cr}^{test} > M_{service})$ or $P(M_{cr}^{test} / M_{service})$, where $M_{service}$ is the moment service force. The estimations of the safety of cracking resistance are significantly higher for samplings of test results of prestressed hollow-core and flat slabs with a developed tension zone than those for prestressed ribbed slabs and roof beams with an insignificant tension zone. The availability of the developed tension zone of prestressed members with the underestimated resources of flexural strength means the increase of the safety of cracking resistance which does not taking into account by building code.

Thus, the flexural and tension strengths of concrete are underestimated in the world building practice. A statistical investigation of these types of concrete strength in connection with the compressive strength of this concrete was carried out by the processing of the data of American test

results of concrete strength. The results of this investigation can be useful for more complete utilization of flexural strength of concrete in connection with the compressive strength of this concrete as applied to thickness design of highway and street concrete pavements.

OBJECTS AND ADVANTAGES

The main object of the present invention is the highway and street concrete pavement of uninterrupted traffic flow and high volumes of truck traffic, designed with the preset strength safety level corresponding to strength safety index β equal at least to about 3, the thickness of claimed pavement determined by the results of fatigue analysis is less by 5-10% than that for this pavement designed according to said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavement, Portland Cement Association EB109P), the reduction of thickness should be achieved due to the more complete utilization of flexural strength of concrete than that provided by the current Portland Cement Association design practice of the utilization of this strength, flexural strength being considered as a random value, the mix design of claimed pavement is determined by the value of the modulus of rupture (MR) required by the thickness design of this pavement according to said Engineering Bulletin.

Another important object of the present invention is highway and arterial street concrete pavement used for moderate volumes of truck traffic designed with the preset strength safety level corresponding to strength safety index β equal at least to about 2.5, thickness of claimed pavement determined by the results of fatigue analysis is less by 5-10% than that for this pavement designed according to said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavement, Portland Cement Association EB109P), the reduction of thickness is should be achieved due to the more complete utilization of flexural strength of concrete than that provided by the current Portland Cement Association design practice of the utilization of this strength, flexural strength being considered as a random value, the mix design of claimed pavement is

determined by the value of the modulus of rupture (MR) required by the thickness design of this pavement according to said Engineering Bulletin.

Still another object of the present invention is roads, residential streets and other streets concrete pavement used for small volumes of truck traffic, designed with the preset strength safety level corresponding to strength safety index β equal at least to about 2, the thickness of claimed pavement determined by the results of fatigue analysis is less by 5-10% than that for this pavement designed according to said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavement, Portland Cement Association EB109P), the reduction of thickness is should be achieved due to the more complete utilization of flexural strength of concrete than that provided by the current Portland Cement Association design practice of the utilization of this strength, flexural strength being considered as a random value, the mix design of claimed pavement is determined by the value of the modulus of rupture (MR) required by the thickness design of this pavement according to said Engineering Bulletin.

The main advantage of present invention is the actual saving of 5-10% of the total consumption of concrete for pavement due to more complete utilization of flexural strength, with mix design of concrete being determined by the value of the modulus of rupture (MR) required by the thickness design of pavement according to said Engineering Bulletin.

Another important advantage of the present invention is the possibility of mix design of concrete determined by the value of modulus of rupture (MR) required by the thickness design of pavement according to said Engineering Bulletin by means of the corresponding value of specified compressive strength of this concrete $f_{c,,}'$ taking into account close statistical connections between compressive and flexural strength.

These and other objects and advantages are attained in the invention, the essence of which consists in taking into account all possibilities for the utilization of the flexural strength of concrete as

completely as possible, considering this strength as a random value in connection with the compressive strength of this concrete.

SUMMARY

The concrete pavement of highways and streets of uninterrupted traffic flow and high volumes of truck traffic, pavement of highways and arterial streets with moderate volumes of truck traffic and pavement of roads, residential streets, and other streets with small volumes of truck traffic are designed with the preset strength safety level corresponding to the value of strength safety index β equal at least to 3.0, 2.5 and 2.0, respectively. Pavement with the stress ratio factor not exceeding 0.5 is used for highways and streets regardless of volumes of truck traffic. Pavement with the stress ratio factor exceeding 0.5 can be used for highways and arterial streets with moderate values of traffic and for roads, residential streets, and other streets with small values of truck traffic.

The thickness of claimed pavements, which is determined by the results of fatigue analysis, is 5-10% less than that provided by the thickness design of these pavements according to said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavements, Portland Cement Association, EB109P). The reduction of the thickness of each claimed pavement is achieved by a more complete utilization of the flexural strength of concrete than that provided by the current Portland Cement Association design practice of the utilization of this strength. A more complete utilization of flexural strength of concrete is provided with the use of results of a statistical investigation of flexural strength of concrete in connection with the compressive strength of this concrete, with concrete strength considered a random value. This investigation is based on the processing of the data of American test results of concrete strength.

More complete utilization of flexural strength of concrete means the use of larger values of the modulus of rupture of concrete (MR) for the thickness design of claimed pavement than that provided by design of this pavement according to said Engineering Bulletin. All mentioned values of the modulus of rupture (MR) are considered as values of specified flexural strength of concrete and

representatives of distribution of density of probability of the flexural strength of this concrete. According to the invention, the distribution of density of probability of flexural strength of concrete is represented by the three values of the modulus of rupture (MR) considered as specified flexural strength of concrete differing by 50 psi and corresponding to one value of specified compressive strength f_c'. The least of these three is the value of the modulus of rupture (MR) required by the thickness design of pavement according to said Engineering Bulletin, with the mix design of concrete being determined by this value of modulus of rupture of concrete (MR). Any of these values of the modulus of rupture of concrete (MR) can be used for thickness design of the claimed pavement of a certain stress ratio factor if the strength safety of pavement designed with the use of this value of the modulus of rupture (MR) corresponds to value of strength safety required according to the invention. Results of fatigue and erosion analysis of pavement designed with the use of any of the mentioned values of the modulus of rupture should be in accordance with requirements of said Engineering Bulletin.

The use of three or even two values of the modulus of rupture (MR) instead of the smallest one of them for fatigue analysis of claimed pavements allows one to obtain a more exact estimation of fatigue strength of these pavements. It allows the reduction of the thickness of these pavements by 5-10% as compared with that provided by the thickness design of these pavements according to said Engineering Bulletin.

Furthermore, consideration of statistical connections between compressive and flexural strength of concrete allows one to estimate value of the modulus of rupture of concrete (MR) required by the thickness design of claimed pavement according to said Engineering Bulletin in connection with the corresponding value of specified flexural strength f_c'. It allows the carrying out of the design of the composition of concrete for claimed pavement by means of the value of the specified compressive strength corresponding to this value of the modulus of rupture. It makes the mix design of

concrete more convenient because the compressive strength of concrete is more commonly used and better studied than flexural strength.

The essence of the present invention is in the more complete utilization of flexural strength of concrete, which is underestimated as a random value in the world building practice. It is applied to the current thickness design procedure provided according to said Portland Cement Association Engineering Bulletin. It should be urgent and can be applied to the new thickness design procedure with change of fatigue and erosion analysis of pavement.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT

The concrete pavement for highways and streets of uninterrupted traffic flow and high volumes of truck traffic is designed with the preset strength safety level corresponding to value of strength safety index β equal at least about to 3, more complete utilization of flexural strength of concrete than that provided by the current Portland Cement Association design practice of utilization of this strength allows to reduce thickness of this pavement by at least 5-10% as compared with that required by the thickness design of this pavement according to said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavements, Portland Cement Association, EB109P), concrete strength is considered as a random value, the mix design of concrete is determined by the value of the modulus of rupture (MR) required by thickness design of this pavement according to said Engineering Bulletin, stress ratio factor α of this pavement does not exceed 0.50 as a most conservative estimation of the flexural endurance limit of concrete defined as a part of the modulus of rupture of concrete (MR).

The choice of required strength safety of concrete pavement is based on the processing of the data of test results of underreinforced prestressed floor and roof slabs. These slabs were designed according to the Russian building code, produced and tested at the Russian plants of precast concrete, mainly at the plants of the Moscow region (Sapozhnikov N. Strength Safety of Precast Reinforced Concrete and Prestressed Structural Members. State Committee of Construction of the USSR Institute

of Information, Moscow, 1989, Table 12). The higher estimation of the strength safety of these slabs corresponding to the value of strength safety index β equal about to 3 was chosen as the required strength safety for claimed concrete pavement for highways and streets of uninterrupted traffic flow and high volumes of truck traffic. As indicated earlier, estimations of the strength safety of underreinforced slabs with the same service loads designed according to the American and Russian building codes are formally the same or nearly the same in spite of the different consumption of tension reinforcement required by the American and Russian building codes. It allows the use of the results of the strength safety analysis of these slabs for the choice of preset strength safety of concrete pavement of highways and streets.

The thickness of claimed pavement is less by 8-10% than that provided by thickness design of this pavement according to said Portland Cement Association Engineering Bulletin EB109P. It is achieved due to a more complete utilization of flexural strength of concrete than that provided by the current Portland Cement Association design practice of the utilization of this strength. More complete utilization of flexural strength of concrete considered as a random value means the increase of the value of the modulus of rupture as compared to that required by the thickness design of pavement according to said Engineering Bulletin. It should be based on the results of the statistical analysis of the flexural strength of concrete and of the strength safety analysis of concrete pavements.

The statistical characteristics of flexural strength in connection with the statistical characteristics of the compressive strength of concrete were obtained by the processing of the data of American test results of 3,650 series of standard cylinders and beams, and American and British tests results of 1,107 series of modified cubes and standard beams. Coefficients of correlation between the compressive and flexural concrete strength are equal to 0.831 and 0.865 for these two samplings of the test results, respectively (Sapozhnikov N. Safety of Precast Reinforced Concrete and Prestressed Structural Members by the Second Limit State (Serviceability Limit State) State Committee of Construction of the USSR Institute of Information, Moscow, 1991, Table 6). Connections between

compressive and flexural concrete strength, which correspond to these values of coefficient of correlation, can be considered statistically significant. It allows one to consider choice of the modulus of rupture of concrete (MR) as a specified flexural strength of concrete for pavement in connection with the specified compressive strength of this concrete.

Mean value of flexural strength of concrete f_r as a function of the mean value of compressive strength f_c of this concrete is equal to $9.42 \sqrt{f_c}$; this estimation is obtained from the comparative analysis of American test results of 3650 series of standard cylinders and beams of the same concrete. The values of the coefficient of variation for compressive and flexural strength of concrete are assumed as the same and equal to 15% for the calculation of the strength safety estimations of concrete pavement.

Since the main estimation of the compressive strength of concrete in the American building practice is cylinder strength, the modified cube strength was assessed as cylinder by dividing into 1.2; cube strength of concrete is higher than that of cylinder by 20% on average. The mean value of the flexural strength of concrete as a function of the mean value of the modified cube compressive strength of this concrete f_{cu}^{mod} is equal to $9.53\sqrt{f_{cu}^{mod}/1.2}$. This estimation of the mean value of flexural strength is obtained from the processing of the data of the test results of 1107 modified cubes and standard beams. As may be seen, the estimations of the mean value of flexural strength of concrete determined depending on the mean values of compressive cylindrical and modified cube strength of this concrete are very close and can be considered equivalent on average. It means that the modified cube compressive strength of concrete should be brought to the cylinder strength of this concrete by dividing by 1.2.

According to said American building code ACI 318, the required average compressive strength of concrete f''_{cr} has to exceed the specified compressive strength f_c' at least by $1.34\mathbf{s}(f_c)$, where $\mathbf{s}\ (f_c)$ is the standard deviation of this strength. Based on the value of coefficient of variation of concrete

compressive strength equal to 15%, this excess can be estimated as 25% of the value of the specified compressive strength f_c'. The required average strength of concrete f_{cr} can be considered as a mean value of this strength f_c. This requirement of said American building code ACI 318 allows the estimation of the mean value of the compressive strength of concrete depending on the value of the specified compressive strength f_c'.

Due to close statistical connections between the compressive and flexural strengths of concrete, the mean value of flexural strength of concrete can be considered as stemming from that of compressive strength. Since the mean value of compressive strength of concrete corresponds to the value of specified compressive strength f_c' the mean value of flexural strength can be considered to be corresponding to this value of the specified compressive strength also. The definition of the specified compressive strength f_c' relates to the 28-day cylindrical strength of concrete. The mean values of the compressive and flexural strengths of concrete determined depending on the specified compressive strength f_c' of this concrete should be considered as statistical characteristics of the 28-day strength of concrete.

As is evident from the above, every value of specified compressive strength f_c' corresponds to the mean values of compressive and flexural concrete strength, with the mean value of flexural strength being determined depending on the mean value of compressive strength of this concrete. It allows the estimation of the value of the modulus of rupture (MR) as a part of the mean value of the flexural strength of concrete depending on the corresponding value of the specified compressive strength f_c', modulus of rupture being considered as the specified flexural strength of concrete.

Like the strength of any structural material, the flexural strength of concrete should be characterized by the specified and design strengths, with the design strength being estimated as a part of the specified strength. Said American building code ACI 318 and documents of the Portland Cement Association do not contain the definition of the specified flexural strength of concrete. According to the current thickness design procedure of concrete pavements, the modulus of rupture

(MR) can be considered as the specified flexural strength of concrete, whereas the allowable flexural stress of concrete defined according to said design procedure as equivalent stress can be considered as the design flexural strength of this concrete. According to said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavements, Portland Cement Association, EB109P), the modulus of rupture (MR) of concrete should be estimated as the average 28-day flexural strength. The value of flexural strength multiplied by 50 psi, which is less than the experimental estimation of the mean value of flexural concrete strength but is nearest to it, should be chosen as the modulus of rupture (MR) of this concrete. If the mean value of flexural strength of concrete is determined according to the present invention depending on the specified compressive strength of this concrete, the procedure of estimation of the value of the modulus of rupture is the same.

Values of the modulus of rupture (MR) equal to 550, 600, 650 and 700 psi used for the thickness design of highway and street concrete pavements were estimated as corresponding to the values of specified compressive strength f_c' equal to 3,000, 3,500, 4,000 and 4,500 psi, respectively. Mentioned values of the modulus of rupture constitute 0.953, 0.962, 0.975 and 0.99 of the mean values of flexural strength corresponding to these values of specified compressive strength f_c', respectively. It is necessary to estimate the strength safety of pavement of a certain stress ratio factor designed using these values of the modulus of rupture of concrete.

The strength safety of concrete pavement as a flexural member is equivalent to safety of the design flexural strength of concrete of this pavement and can be estimated as a probability $P(f_r > \alpha MR)$, where f_r is a flexural strength of concrete considered as a random value, α is the stress ratio factor of highway and street concrete pavement, and αMR is the design flexural strength of concrete estimated as a part of the modulus of rupture of this concrete. The stress ratio factor of pavement is the ratio between the equivalent stress of concrete determined depending on the trial thickness and subbase-subgrade *k* factor of this pavement and the value of the modulus of rupture. The

equivalent stress of concrete as allowable flexural stress of concrete pavement equal to αMR can be considered the design flexural strength of concrete.

The strength safety level of pavement is not taken into account directly by the current thickness design procedure of concrete pavement. The thickness design procedure of highway and street concrete pavement requires a choice of the trial thickness, usually determined by the design practice, and the value of the modulus of rupture of concrete (MR) considered as a specified compressive strength of concrete. This procedure includes the checking of the sufficiency of pavement of the trial thickness in terms of the requirements for the fatigue and erosion analysis of this pavement according to said Portland Cement Association Engineering Bulletins EB109P.

The fatigue analysis of highway and street concrete pavement is carried out depending on the stress ratio factor of this pavement regardless of the value of the modulus of rupture. The value of the stress ratio factor of pavement is limited by the requirements for the fatigue analysis of this pavement. The erosion resistance of pavement depends on the values of the modulus of rupture and the stress ratio factor indirectly.

According to the invention, the stress ratio factor α of highway and street concrete pavement used regardless of the truck traffic volumes should not exceed 0.50 as a value of the flexural endurance limit of concrete defined as a part of the modulus of rupture of concrete (MR). The definition of the flexural endurance limit of concrete presumes the possibility of unlimited repetitions of loads, if the stress ratio factor of claimed pavement does not exceed the value of this limit. The estimation of the flexural endurance limit of concrete equal to 0.5MR is based on a great volume of American tests of concrete and can be considered conservative in the US building practice. However, the results of the fatigue analysis of pavements with this limitation of the stress ratio factor often do not meet the requirements of said Engineering Bulletin. Stress ratio factor of highway and street concrete pavements of uninterrupted traffic flow and high volumes of truck traffic with high volumes of truck traffic is usually in the range from 0.3 to 0.4. These requirements can be considered the most

rigid criterion of the sufficiency of concrete pavement in terms of its fatigue resistance. The strength safety of pavement with the value of the stress ratio factor equal to 0.5 defined as a probability $P(f_r > 0.50\ MR)$ is considered as the strength safety of claimed pavement with a high volume of truck traffic; the strength safety estimations of pavements with smaller values of the stress ratio factor are higher.

The availability of the statistical characteristics of the flexural strength of concrete connected with the corresponding values of the modulus of rupture (MR) allows the assessment of the estimations of the strength safety of pavement. The estimations of the strength safety of pavement were calculated depending on the values of the modulus of rupture and the stress ratio factor. The results of these calculations are presented in the Table 1. The estimations of the strength safety of pavement with the stress ratio factor equal to 0.5 as probabilities $P(f_r > 0.5MR)$ designed with the use of values of the modulus of rupture equal to 550, 600, 650 and 700 psi correspond to values of the strength safety index β equal to 3.49, 3.45, 3.41, 3.37, respectively. All mentioned estimations of the strength safety of claimed pavement exceed the required strength safety level corresponding to the value of the strength safety index β equal to 3. It means the availability of excessive resources of the strength safety of pavement and a possibility of a more complete utilization of the flexural strength of concrete for the thickness design of this pavement.

As indicated earlier, a more complete utilization of the flexural strength of concrete considered as a random value means the use of greater values of the modulus of rupture (MR) than that required by the thickness design of this pavement according to said Engineering Bulletin. In so doing the mix design of concrete is determined by the value of the modulus of rupture required by the thickness design of this pavement according to said Engineering Bulletin. According to the invention, the value of the modulus of rupture provided by the current thickness design procedure and increased estimations of the modulus of rupture are representative of the distribution of the density of the probability of the flexural strength of concrete. Due to close statistical connections between the compressive and flexural strength of concrete, the distribution of the density of probability of flexural

strength of concrete can be considered as corresponding to the specified compressive strength of this concrete f_c' as well as the distribution of the density of probability of compressive strength of this concrete. As a result, all mentioned estimations of the modulus of rupture of this concrete as representatives of distribution of density of probability of flexural strength of concrete can be considered to be corresponding to this value of the specified compressive strength of concrete f_c'. In so doing, the value of the modulus of rupture of concrete provided by the current thickness design procedure just corresponds to the mean value of the flexural strength and the specified compressive strength of this concrete

The distribution of the density of the probability of the flexural strength of concrete can be represented by a few values of the modulus of rupture (MR) considered as the specified flexural strength of this concrete and corresponding to the one value of specified compressive strength f_c'. Any of these values of the modulus of rupture of concrete (MR) can be used for the thickness design of claimed pavement of certain stress ratio factor, if the estimation of the strength safety of this pavement designed with the use of this value of the modulus of rupture is not less than the strength safety level required according to the invention. In so doing the strength safety of pavement is estimated depending on the values of the modulus of rupture and the stress ratio factor of pavement.

According to the invention, three values of specified flexural strength of concrete (MR) differing by 50 psi are considered as representatives of distribution of density of probability of flexural strength of concrete corresponding to the one value of specified compressive strength f_c'. The least of these three is the value of modulus of rupture (MR) required by the thickness design of pavement according to said Portland Cement Association Engineering Bulletin, and just this value of modulus of rupture (MR) corresponds to mentioned value of specified compressive strength f_c'. Two other values of modulus of rupture (MR) of these three should be considered as corresponding to this value of specified compressive strength f_c' also, because they are considered as representatives of distribution of density of probability of flexural strength of concrete corresponding to this value of specified

compressive strength. According to the invention, all three values of modulus of rupture (MR) can be used for fatigue analysis of claimed pavement, if estimations of strength safety of pavement designed with the use of these values of modulus of rupture correspond to strength safety level required according to the invention.

Strength safety estimations of concrete pavements in the form of strength safety index β are presented in Table 2 depending on the value of stress ratio factor, value of specified compressive strength f_c' and corresponding three values of modulus of rupture (MR) differing by 50 psi. Three estimations of strength safety of pavement in form of strength safety index β correspond to these three values of specified flexural strength of concrete (MR) stemmed from one value of specified compressive strength of this concrete f_c'. The least of these three estimations of strength safety of pavement corresponds to value of modulus of rupture (MR) required by the thickness design of this pavement according to said Portland Cement Association Engineering Bulletin. Calculation of estimations of strength safety of concrete pavements presented in the Table 2 was carried out with the use of the mean value f_r and standard deviation $s(f_r)$ of flexural strength of concrete equal to $9.42\sqrt{f_c}$ and $0.15f_r$, respectively. The mean value of compressive strength of concrete f_c is considered as required average strength defined according to said American building code ACI 318 (item 5.3.2.1).

As can be seen from the Table 2, estimations of strength safety of pavement designed with the use of three values of modulus of rupture (MR) with the difference of 50 psi corresponding to one value of specified compressive strength of concrete f_c' are different. However, this difference is statistically insignificant at least for claimed pavement with stress ratio factor not exceeding 0.50. Estimations of strength safety of pavement of this limitation of stress ratio factor designed with the use of any of these groups of three values of modulus of rupture (MR) exceed the strength safety level required according to the invention corresponding to value of strength safety index β equal at least to about 3 or very close to this value. It means the availability of excessive resources of strength safety of

pavement of stress ratio factor not exceeding 0.50 designed according to said Portland Cement Association Engineering Bulletin and possibility of more complete utilization of flexural strength of concrete for thickness design of this pavement. All three values modulus of rupture (MR) of these groups can be used for fatigue analysis of claimed pavement.

Fatigue analysis of claimed pavement is carried out in framework of said Portland Cement Association Engineering Bulletin with the consecutive use of three values of modulus of rupture (MR) considered as specified flexural strength and differing by 50 psi. The least of these three values is the value of modulus of rupture (MR) required by thickness design of pavement according to said Portland Cement Association Engineering Bulletin. Results of fatigue and erosion analysis of claimed pavement should meet requirements of said Portland Cement

The consecutive use of three values of modulus of rupture (MR) corresponding to one value of specified compressive strength of this concrete for fatigue analysis of claimed pavement allows to reduce thickness of claimed pavement by 8-10% as compared with that provided by the thickness design of this pavement according to said Portland Cement Association Engineering Bulletin. It can be presented by the example from said Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavement, Portland Cement Association, EB109P, p. 12).

Concrete pavement with the trial thickness 9.5 inches and modulus of rupture of concrete (MR) equal to 650 psi for four-lane Interstate road with large volume of truck traffic has stress ratio factor equal to 0.317 under single axle. Results of fatigue and erosion analysis of this pavement are in accordance with the requirements of said Engineering Bulletin, thickness of pavement being controlled by results of fatigue analysis.

Thickness design of claimed pavement according to said Engineering Bulletin is considered as a first step of design procedure according to the invention. According to the invention, value of modulus of rupture (MR) equal to 650 psi required by thickness design of pavement according to said Engineering Bulletin just corresponds to value of specified compressive strength f_c' equal to 4,000 psi.

This value of modulus of rupture (MR) is considered as the least of three values of modulus of rupture differing by 50 psi and equal to 650, 700 and 750 psi. These three values of modulus of rupture (MR) are considered as corresponding to one value of specified compressive strength of this concrete f_c' equal to 4,000 psi (Table 2). According to the invention, any of these three values of specified flexural strength (MR) can be used for fatigue analysis of pavement, if strength safety of pavement with stress ratio factor equal to 0.5 designed with the use of this value of specified flexural strength is assessed as sufficient.

Estimations of strength safety of pavement with stress ratio factor equal to 0.5 designed with the use of three values of specified flexural strength (MR) equal to 650,700 and 750 psi correspond to values of strength safety index β equal to 3.41, 3.16 and 2.91, respectively (Table 2). All mentioned estimations of strength safety of pavement exceed or are very close statistically to required strength safety level corresponding to value of strength safety index β equal at least about to 3. It means the availability of excessive resources of strength safety of pavement and possibility of more complete utilization of flexural strength of concrete for thickness design of this pavement. At the same time, estimations of strength safety of pavement with the stress ratio factor equal to 0.317 designed with the use of these values of specified flexural strength are considerably higher. It means that all these three values of modulus of rupture can be used for fatigue analysis of claimed pavement.

The use of value of modulus of rupture (MR) equal to 700 psi instead of 650 psi for fatigue analysis of pavement in framework of said Portland Cement Association Engineering Bulletin allows to decrease the thickness of this pavement from 9.5 to 9 inches without change of stress ratio factor. The use of value of modulus of rupture (MR) equal to 750 psi instead of 700 psi allows to reduce the thickness of this pavement to 8.5 inches instead of 9.0 inches. Stress ratio factor of pavement with the least value of thickness is equal to 0.322. The consecutive use of second and third of three values of specified flexural strength (MR) differing by 50 psi allows to reduce trial thickness of pavement by 8.94% as compared with that for this pavement designed according to said Portland Cement

Association Engineering Bulletin. In so doing, the strength safety of pavements is sufficient, results of fatigue and erosion analysis of pavement are in accordance with requirements of said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavements, Portland Cement Association, EB109.01P, 1995).

Design 1 of said Engineering Bulletin (page 21) includes five decisions of Interstate concrete pavement with granular and cement-treated 4-inch thickness subbase, with doweled and aggregate-interlock joints, with and without concrete shoulders. Thickness of pavements of design1A and design1C is determined by the requirements of fatigue analysis. According to requirements of said Portland Cement Association Engineering Bulletin thickness of these pavements constitute 9.5 and 8.5 inches, respectively. More complete utilization of flexural strength of concrete allows to reduce thickness of these pavements by 1 inch, i. e. by the 10.5 and 11.7%, respectively. Estimations of strength safety of pavements of reduced thickness exceed strength safety level required according to the invention, results of fatigue and erosion analysis of pavement are in accordance with the requirements of said of said Portland Cement Association Engineering Bulletin.

According to the invention, more complete utilization of flexural strength of concrete considered as a random value allows to obtain more accurate estimation of fatigue strength of pavement in framework of said Engineering Bulletin. As a result, the thickness of claimed pavement can be reduced by 8-10% as compared with that required by the design according to said Engineering Bulletin.

The essence of present invention is in the more complete utilization of flexural strength of concrete than that provided by the current design practice. It is applied to the thickness design of highway and street concrete pavement of high volume of truck traffic with fatigue analysis performed according to said Portland Cement Association Engineering Bulletin, and can be applied to the thickness design of this pavement with other methods of fatigue analysis.

OPERATION OF PREFERRED EMBODIMENT

According to present invention, thickness design of claimed highway and street concrete pavement of uninterrupted traffic flow and high volumes of truck traffic is carried out in format of said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavements, Portland Cement Association, EB109P) with more complete utilization of flexural strength of concrete than that provided by the current Portland Cement Association design practice of the utilization of this strength. Fatigue analysis of claimed pavement should be carried out with the consecutive use of the three values of modulus of rupture (MR) differing by 50 psi and corresponding to one value of specified compressive strength of concrete. The least of these three is the value of modulus of rupture (MR) required by the thickness design of pavement according to said Engineering Bulletin.

According to the invention, first step of thickness design of claimed pavement is completely in accordance with the design procedure of said Engineering Bulletin. This procedure of thickness design of pavement includes the choice of trial thickness and modulus of rupture (MR), determination of value of equivalent stress depending on trial thickness and subgrade-subbase k value, stress ratio factor and erosion factor of pavement. Results of fatigue and erosion analysis of pavement of trial thickness should meet requirements of said Engineering Bulletin.

Next step of thickness design of claimed pavement is the determination of specified compressive strength of concrete fc' just corresponding to value of modulus of rupture (MR) required by the thickness design of pavement according to said Engineering Bulletin (Table 2). Values of modulus of rupture (MR) used for thickness design of pavement according to said Portland Cement Association Engineering Bulletin and equal to 550, 600, 650 and 700 psi are considered as just corresponding to values of specified compressive strength fc' equal to 3,000, 3,500, 4,000 and 4,500 psi, respectively. According to the invention, two other values of modulus of rupture of this concrete (MR) differing by 50 psi are considered as corresponding to this value of specified compressive strength also. Thus, each value of specified compressive strength fc' corresponds to three values of

modulus of rupture (MR). The least of these three is the modulus of rupture (MR) required by thickness design of this pavement according to said Portland Cement Association Engineering Bulletin. Since strength safety of claimed pavement as a probability P(f_r > 0.5MR) corresponds to values strength safety index β exceeding 3 or very close to this value, all three values of modulus of rupture can be used for thickness design of pavement.

According to the invention, the consecutive steps of thickness design of claimed pavement should be provided by trial-error method. Two next steps of thickness design of claimed pavement should be carried out with the use of second and third values of modulus of rupture of the three corresponding to one value of specified compressive strength of concrete fc' for fatigue analysis of this pavement. Trial thickness of pavement designed with the use of second and third of these three values is less usually by 1/2" as compared with the thickness of pavement corresponding to less value of modulus of rupture. Results of fatigue and erosion analyses of pavement with the trial thickness should meet requirements of said Portland Cement Association Engineering Bulletin

ADDITIONAL EMBODIMENT OF INVENTION

Concrete pavement for highways and arterial streets with the moderate volumes of truck traffic is designed with the preset strength safety level corresponding to value of strength safety index β equal at least about to 2.5. Thickness of claimed pavement controlled by the results of fatigue analysis of this pavement is less by 8-10% than that provided by the thickness design of this pavement according to said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavements, Portland Cement Association, EB109P). It is achieved due to the more complete utilization of flexural strength of concrete than that provided by the current Portland Cement Association design practice of utilization of this strength, flexural strength of concrete being considered as a random value. Stress ratio factor α of pavement exceeds 0.50 as a value of flexural endurance limit of concrete defined as a part of modulus of rupture of concrete (MR). Mix design of

concrete is determined by the value of modulus of rupture (MR) required by the thickness design of this pavement according to said Engineering Bulletin.

Strength safety level of pavement is defined as a probability P(fr > αMR), where fr is a flexural strength of concrete considered as a random value. The choice of the required strength of claimed pavement is based on the analysis of test results of underreinforced prestressed floor and roof slabs (Sapozhnikov N. Strength Safety of Precast Reinforced Concrete and Prestressed Structural Members. State Committee of Construction of the USSR Institute of Information, Moscow, 1989, Table 12). Higher estimation of strength safety of prestressed floor and roof slabs of the same spans produced on the one plant, which corresponds to strength safety index β equal to 3, was chosen as required strength safety for concrete pavement of highways and streets of uninterrupted traffic flow and high volumes of truck traffic. The least estimation of strength safety of these structural members, which corresponds to strength safety index β equal to 2.5, was chosen as required strength safety for concrete pavement of highway and arterial streets with the moderate volumes of truck traffic. Strength safety index β equal to 2.5 corresponds to estimation of strength safety equal to 0.9938.

Thickness design procedure of claimed pavement for highways and material streets with the moderate volumes of truck traffic and operation of embodiment of this invention are the same as for pavement for highways and streets used regardless of the volumes of truck traffic. The difference is in the required strength safety level and in the range of stress ratio factor.

Estimations of strength safety of pavement with the different values of stress ratio factor designed with the use of values of modulus of rupture equal to 550, 600, 650 and 700 psi are presented in the Table 1. These estimations for pavements with the stress ratio factor equal to 0.5 and 0.7 designed with the use of these values of modulus of rupture (MR) correspond to strength safety index β equal to 3.49, 3.45, 3.41, 3.37 and 2.22, 2.18, 2.11, 2.05, respectively. As can be seen from this Table, all estimations of pavement with the stress ratio factor in the range from 0.5 to 0.6 can be

considered as excessive in terms of strength safety of claimed pavement, since they exceed required strength safety level of this pavement. Availability of excessive resources of strength safety of concrete pavement means the possibility of more complete utilization of flexural strength of concrete for thickness design of this pavement.

According to the invention, flexural strength of concrete considered as a random value is represented by the three values of modulus of rupture (MR) corresponding to one value of specified compressive strength fc' (Table 2). The least of these three is the value of modulus of rupture (MR) required by thickness design of pavement according to said Portland Cement Association Engineering Bulletin. Fatigue analysis of pavement should be provided in the framework of said Engineering Bulletin with the consecutive use of these values of modulus of rupture (MR). Any of these values of modulus of rupture of concrete can be used for fatigue analysis of claimed pavement, if strength safety of pavement designed with the use of this value of modulus of rupture (MR) corresponds to strength safety indexes β equal at least to about 2.5.

Strength safety of pavement and corresponding possibility of more complete utilization of flexural strength of concrete for fatigue analysis of this pavement depend on the value of stress ratio factor of pavement. It can be considered on the example of concrete pavement designed according to said Portland Cement Association Engineering Bulletin with the use of value of modulus of rupture (MR) equal to 650 psi. This value of modulus of rupture (MR) just corresponds to value of specified compressive cylindrical strength fc' equal to 4,000 psi. According to the invention, three values of modulus of rupture (MR) equal to 650, 700 and 750 psi are considered as corresponding to this value of specified compressive strength. The least of these three is the value of modulus of rupture (MR) required by thickness design of this pavement according to said Engineering Bulletin.

Estimations of strength safety of pavement with the stress ratio factor equal to 0.55 designed with the use of these three values of modulus of rupture MR) correspond to values of strength safety index β equal to 3.09, 2.81 and 2.54, respectively (Table 2). All three estimations of strength safety

exceed required strength safety level for claimed pavement with the moderate volumes of truck traffic. It means that these three values of modulus of rupture (MR) can be used for fatigue analysis of claimed pavement in the framework of said Portland Cement Association Engineering Bulletin.

Estimations of strength safety of this pavement with the stress ratio factor equal to 0.6 designed with the use of these three values of specified flexural strength (MR) correspond to values of strength safety index β equal to 2.76, 2.46 and 2.16. It means that only two values of modulus of rupture (MR) equal to 650 and 700 psi can be used for fatigue analysis of claimed pavement with the moderate volume of truck traffic. The third value of three equaled to 750 psi can be used for fatigue analysis of pavement with the small volumes of truck traffic.

Estimations of strength safety of this pavement with the stress ratio factor equal to 0.65 designed with the use of these three values of modulus of rupture (MR) correspond to values of strength safety index β equal to 2.44, 2.11 and 1.79. It means that more complete utilization of flexural strength of this pavement is impossible. This pavement should be designed completely according to said Portland Cement Association Engineering Bulletin.

According to the invention, the consecutive steps of thickness design of claimed pavement corresponding to these three values of modulus of rupture (MR) differing by 50 psi should be provided by trial-error method. Trial thickness of pavement designed with the use of second and third of these three values should be less usually by 1/2" as compared with the thickness of pavement corresponding to less value of modulus of rupture. Results of fatigue and erosion analyses of pavements with the trial thickness should meet requirements of said Portland Cement Association Engineering Bulletin.

The essence of present invention is in the more complete utilization of flexural strength of concrete than that provided by the current design practice. It is applied to the thickness design of concrete pavement of highways and arterial streets of moderate volumes of truck traffic with fatigue analysis performed according to said Portland Cement Association Engineering Bulletin, and can be applied to the thickness design of this pavement with other methods of fatigue analysis.

ONE MORE ADDITIONAL EMBODIMENT OF INVENTION

Concrete pavement for roads, residential streets, and other streets with the small volumes of truck traffic is designed with the preset strength safety level corresponding to value of strength safety index β equal at least about to 2.0. Thickness of claimed pavement controlled by the results of fatigue analysis of this pavement is less by 8-10% than that provided by thickness design of this pavement according to said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavements, Portland Cement Association, EB109P). It is achieved due to the more complete utilization of flexural strength of concrete than that provided by the current Portland Cement Association design practice of utilization of this strength, concrete strength being considered as a random value. Stress ratio factor β of pavement exceeds 0.50 as a value of flexural endurance limit of concrete defined as a part of modulus of rupture of concrete (MR). Mix design of concrete is determined by the value of modulus of rupture (MR) required by the thickness design of pavement according to said Engineering Bulletin.

Strength safety level of pavement defined as a probability $P(f_r > \alpha MR)$, where f_r is a flexural strength of concrete considered as a random value. Required strength safety level of concrete pavement for roads, residential streets, and other streets with the small volumes of truck traffic corresponding to strength safety index β equal at least to about 2.0 was chosen on the basis of experience of long time service precast reinforced and prestressed road slabs. (Berdichevsky G.I, Sapozhnikov N.Ya. Design Features of Bent Concrete Constructions with the Economical Responsibility. Moscow, 1982, The Ninth International Congress of FIP, Stockholm, June 6-18, 1982, USSR Member Group), (Sapozhnikov N. Safety of Precast Reinforced Concrete and Prestressed Structural Members by the Second Limit State (Serviceability Limit State). State Committee of

Construction of the USSR Institute of Information, Moscow, 1991, Table 6). Strength safety index β equal to 2.0 corresponds to estimation of strength safety equal to 0.9772.

Thickness design procedure of claimed pavement for roads, residential streets, and other streets with the small volumes of truck traffic and operation of embodiment of this invention are the same as for pavement for highways and arterial streets with the moderate volumes of truck traffic. The difference is in the required strength safety level of claimed pavement.

Estimations of strength safety of pavement with the different values of stress ratio factor designed according to said Portland Cement Association Engineering Bulletin with the use of values of modulus of rupture equal to 550, 600, 650 and 700 psi are presented in the Table 1. As can be seen from the Table 1, strength safety of concrete pavement with the stress ratio factor in the range from 0.5 to 0.60 can be considered as excessive; these estimations correspond to strength safety index β exceeding required strength safety level of claimed pavement. Availability of excessive resources of strength safety of concrete pavement means the possibility of more complete utilization of flexural strength of concrete of this pavement.

According to the invention, flexural strength of concrete considered as a random value is represented by the three values of modulus of rupture (MR) corresponding to one value of specified compressive strength f_c'. The least of these three values is the value of modulus of rupture (MR) required by thickness design of pavement according to said Engineering Bulletin. Fatigue analysis of pavement should be carried out in the framework of said Engineering Bulletin with the consecutive use of these values of modulus of rupture (MR). Any of these values of modulus of rupture of concrete can be used for fatigue analysis of claimed pavement of certain stress ratio factor, if strength safety of pavement designed with the use of this value of modulus of rupture (MR) strength safety indexes β equal to at least about 2.0.

More complete utilization of flexural strength of concrete means the use of greater values of modulus of rupture (MR) for thickness design of claimed pavement than that required by thickness design of this pavement according to said Portland Cement Association Engineering Bulletin. For example, concrete pavement designed according to said Engineering Bulletin with the use of value of modulus of rupture (MR) equal to 650 psi is considered. This value of modulus of rupture (MR) just corresponds to value of specified compressive cylindrical strength f_c' equal to 4,000 psi. According to the invention, three values of modulus of rupture (MR) equal to 650, 700 and 750 psi are considered as corresponding to this value of specified compressive strength. Value of modulus of rupture (MR) equal to 650 psi required by thickness design of this pavement according to said Portland Cement Association Engineering Bulletin is the least of these three.

Estimations of strength safety of pavement with the stress ratio factor equal to 0.55 and 0.6 designed with the use of these three values of specified flexural strength (MR) correspond to values of strength safety index β equal to 3.09, 2.81, 2.54, and 2.76, 2.46, 2.16, respectively (Table 2). All three estimations of strength safety exceed required strength safety level for claimed pavement corresponding to strength safety index β equal at least to about 2.0. According to the invention, it means that these three values of modulus of rupture of concrete (MR) can be used for fatigue analysis of claimed pavement in the framework of said Portland Cement Association Engineering Bulletin.

Estimations of strength safety of this pavement with the stress ratio factor equal to 0.65 correspond to the values of strength safety index β equal to 2.44, 2.11 and 1.79. It means that only two values of modulus of rupture (MR) equal to 650 and 700 psi can be used for fatigue analysis of claimed pavement.

Estimations of strength safety of pavement with the stress ratio factor equal to 0.70 designed with the use of these three values of specified flexural strength (MR) correspond to values of strength safety index β equal to 2.11, 1.76 and 1.41, respectively. It means that more complete utilization of

flexural strength of this pavement is impossible. This pavement should be designed completely according to said Portland Cement Association Engineering Bulletin.

According to the invention, the consecutive steps of thickness design of claimed pavement corresponding to these three values of modulus of rupture (MR) differing by 50 psi should be provided by trial-error method. Trial thickness of pavement designed with the use of second and third of these three values should be less usually by 1/2" as compared with the thickness of pavement corresponding to less value of modulus of rupture. Results of fatigue and erosion analyses of pavements with the trial thickness should meet requirements of said Portland Cement Association Engineering Bulletin.

The essence of present invention is in the more complete utilization of flexural strength of concrete than that provided by the current design practice. It is applied to the thickness design of concrete pavement of roads, residential streets, and other streets of small volumes of truck traffic with fatigue analysis performed according to said Portland Cement Association Engineering Bulletin, and can be applied to the thickness design of this pavement with other methods of fatigue analysis.

CONCLUSION

Thus, claimed concrete pavement of highways and streets of uninterrupted traffic flow and high volumes of truck traffic, concrete pavement of highways and arterial streets with the moderate volumes of truck traffic and concrete pavement of roads, residential streets, and other streets with the small volumes of truck traffic are designed with the preset strength safety level corresponding to value of strength safety index β equal at least to about 3.0, 2.5 and 2.0, respectively. These estimations of strength safety are considered as criteria of sufficiency of claimed pavements in terms of strength safety.

Thickness of these pavements controlled by the results of fatigue analysis is less by 5-10% than that provided by thickness design of these pavements according to said Portland Cement Association Engineering Bulletin (Thickness Design for Concrete Highway and Street Pavements,

Portland Cement Association, EB109P). It is achieved due to more complete utilization of flexural strength than that provided by the current Portland Cement Association design practice of utilization of this strength, concrete strength being considered as a random value. Mix design of concrete is determined by the value of modulus of rupture (MR) required by the thickness design of this pavement according to said Engineering Bulletin.

More complete utilization of flexural strength of concrete considered as a random value means the use of larger values of modulus of rupture (MR) than that provided by thickness design of this pavement according to said Portland Cement Association Engineering Bulletin. According to the invention, any value of modulus of rupture (MR) considered as specified flexural strength of concrete can be used for thickness design of claimed pavement, if estimation of strength safety of pavement of certain stress ratio factor designed with the use of this value of modulus of rupture (MR) corresponds to strength safety level required according to the invention. Required strength safety levels of claimed pavements were chosen basing on the strength safety analysis of structural members (Sapozhnikov N. Strength Safety of Precast Reinforced Concrete and Prestressed Structural Members. State Committee of Construction of the USSR Institute of Information, Moscow, 1989, Tables 12 and 24), (Berdichevsky G.I, Sapozhnikov N.Ya. Design Features of Bent Concrete Constructions with the Economical Responsibility. Moscow, 1982, The Ninth International Congress of FIP, Stockholm, June 6-18, 1982, USSR Member Group). Estimation of degree of utilization of flexural strength of concrete and design procedure of its more complete utilization as a random value is based on the statistical investigation of flexural strength of concrete in connection with the compressive strength of this concrete. This investigation was carried out by the processing data of American test results of concrete strength (Sapozhnikov N. Safety of Precast Reinforced Concrete and Prestressed Structural Members by the Second Limit State (Serviceability Limit State). State Committee of Construction of the USSR Institute of Information, Moscow, 1991, Table 6).

Possibility of the use of three or even two values of modulus of rupture (MR) differing by 50 psi instead the one the least of these three for fatigue analysis of claimed pavement means the significant increase of degree of utilization of flexural strength of concrete, the least of these three being the value of modulus of rupture required by the thickness design of this pavement according to said Engineering Bulletin. It allows to obtain more exact estimation of fatigue strength of concrete and, as a result, to reduce the thickness of claimed pavement by 5-10% as compared with that provided by thickness design of these pavements according to said Engineering Bulletin. Results of fatigue and erosion analyses of pavement with the trial thickness should meet requirements of said Portland Cement Association Engineering Bulletin.

The essence of present invention is in the more complete utilization of flexural strength of concrete, which is underestimated as a random value in the world building practice. It is applied to current thickness design procedure provided according to said Portland Cement Association Engineering Bulletin. It should be urgent and can be applied to new thickness design procedure with change of fatigue and erosion analysis of pavement.

It will be understood that although preferred embodiments of the present invention have been shown and described, various modifications thereof will be apparent to those skilled in art, and, accordingly, the scope of the present invention should be defined only by the appended claims and equivalents thereof.

Table 1. The strength safety estimations of highway and street concrete pavement in form of strength safety index β as a function of stress ratio factor of pavement, specified compressive strength of concrete fc' and values of modulus of rupture (MR) considered as a specified flexural strength of this concrete.

Stress ratio factor	Specified compressive concrete strength fc' (psi)			
	3,000	3,500	4,000	4,500
	Modulus of rupture (MR) considered as specified flexural concrete strength (psi)			
	550	600	650	700
0.20	5.40	5.38	5.36	5.35
0.30	4.76	4.74	4.71	4.68
0.40	4.12	4.10	4.06	4.02
0.50	3.49	3.45	3.41	3.37
0.55	3.17	3.14	3.09	3.04
0.60	2.85	2.82	2.76	2.70
0.65	2.53	2.50	2.44	2.37
0.70	2.22	2.18	2.11	2.05

Remark to the Table 1: The values of modulus of rupture of concrete equal to 550, 600, 650, and 700 psi are considered as just corresponding to the values of specified compressive strength of concrete fc' equal to 3,000, 3,500, 4,000, and 4,500 psi, respectively.

Table 2. The strength safety estimations of highway and street concrete pavement in form of strength safety index β as a function of stress ratio factor of pavement, specified compressive strength of concrete fc' and values of modulus of rupture (MR) considered as a specified flexural strength of this concrete.

Stress ratio factor	Specified compressive concrete strength fc' (psi)											
	3,000			3,500			4,000			4,500		
	Modulus of rupture (MR) considered as specified flexural concrete strength (psi)											
	550	600	650	600	650	700	650	700	750	700	750	800
0.20	5.40	5.28	5.16	5.38	5.27	5.17	5.36	5.26	5.16	5.35	5.25	5.16
0.30	4.76	4.58	4.41	4.74	4.58	4.42	4.71	4.51	4.41	4.68	4.55	4.40
0.40	4.12	3.89	3.66	4.10	3.88	3.67	4.06	3.86	3.66	4.02	3.83	3.65
0.50	3.49	3.20	2.91	3.45	3.19	2.92	3.41	3.16	2.91	3.37	3.13	2.89
0.55	3.17	2.85	2.53	3.14	2.84	2.55	3.09	2.81	2.54	3.04	2.78	2.51
0.60	2.85	2.51	2.16	2.82	2.50	2.18	2.76	2.46	2.16	2.70	2.42	2.14
0.65	2.53	2.16	1.78	2.50	2.15	1.80	2.44	2.11	1.79	2.37	2.07	1.76
0.70	2.22	1.81	1.41	2.18	1.80	1.43	2.11	1.76	1.41	2.05	1.71	1.38

Remark to the Table 2: Three values of modulus of rupture (MR) corresponding to one value of specified compressive concrete strength fc' are considered as specified flexural strength of concrete and representatives of distribution of density of probability of flexural strength. The less of these three is the value of modulus of rupture required by thickness design of this pavement according to Portland Cement Association Engineering Bulletin (Thickness Design of Concrete Highways and Street Pavement, Portland Cement Association, EB109P).